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Computational Modeling of Underground Tunnel Response

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13. ABSTRACT *(Maximum 200 words)*
This technical report describes computational modeling of underground tunnel response in support of the Underground Technology Program (UTP) which is a multi-year investigation into the vulnerability of underground structures. The overall program includes computational modeling, material modeling, laboratory testing, and field testing to improve the ability to predict the response and failure of underground structures subjected to ground shock due to near-surface explosions. The emphasis is on deeply buried tunnels with little or no reinforcement.

The computational modeling effort involved three major areas of investigation: 1) benchmark activity, 2) parametric study and 3) laboratory test simulation. The benchmark activity was a step-by-step series of idealized problems which addressed various aspects of tunnel response in jointed rock masses. The parametric study considered the systematic sensitivity of loading environment, material characterization and geometric conditions as well as computational approaches on tunnel response. Numerical simulation of the SRI International lab-scale HE experiments on tunnel response in intact limestone was conducted to correlate calculational approaches with data.

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PREFACE

The calculational work described herein was performed by personnel of Titan (formerly California) Research and Technology (TRT) Division of the Titan Corporation during the period 10 August 1990 to 10 September 1994 for the Defense Nuclear Agency (DNA). The technical effort was supported under Contract No. DNA001-90-C-0141 as part of the Underground Technology Program (UTP). Dr. Paul E. Senseny (DNA/SPSD) served as the Contract Technical Monitor.

Dr. Y. Marvin Ito, TRT Program Manager, was principal investigator for this research effort on computational modeling of underground tunnel response. Dr. Russell H. England and Mr. Yoshio Muki developed and implemented the material models for computational applications. Messrs. Sang B. Choi, Alois Dorfmann and Yoshio Muki performed finite element modeling and calculations and assisted in the analyses.

CONVERSION TABLE

Conversion factors for U.S. customary to metric (SI) units of measurement

To Convert From	To	Multiply
angstrom	meters (m)	1.000 000 X E–10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E+2
bar	kilo pascal (kPa)	1.000 000 X E+2
barn	meter^2 (m^2)	1.000 000 X E–28
British Thermal unit (thermochemical)	joule (J)	1.054 350 X E+3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermochemical)/cm^2	mega joule/m^2(MJ/m^2)	4.184 000 X E–2
curie	giga becquerel (GBq)*	3.700 000 X E+1
degree (angle)	radian (rad)	1.745 329 X E–2
degree Fahrenheit	degree kelvin (K)	$t_K=(t^\circ f + 459.67)/1.8$
electron volt	joule (J)	1.602 19 X E–19
erg	joule (J)	1.000 000 X E–7
erg/second	watt (W)	1.000 000 X E–7
foot	meter (m)	3.048 000 X E–1
foot–pound–force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E–3
inch	meter (m)	2.540 000 X E–2
jerk	joule (J)	1.000 000 X E+9
joule/kilogram (J/Kg) (radiation dose absorbed)	Gray (Gy)	1.000 000
kilotons	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E+3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E+3
ktap	newton–second/m^2 (N–s/m^2)	1.000 000 X E+2
micron	meter (m)	1.000 000 X E–6
mil	meter (m)	2.540 000 X E–5
mile (international)	meter (m)	1.609 344 X E+3
ounce	kilogram (kg)	2.834 952 X E–2
pound–force (lbf avoirdupois)	newton (N)	4.448 222
pound–force inch	newton–meter (N·m)	1.129 848 X E–1
pound–force/inch	newton/meter (N/m)	1.751 268 X E+2
pound–force/foot^2	kilo pascal (kPa)	4.788 026 X E–2
pound–force/inch^2 (psi)	kilo pascal (kPa)	6.894 757
pound–mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E–1
pound–mass–foot^2 (moment of inertia)	kilogram–meter^2 (kg·m^2)	4.214 011 X E–2
pound–mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601 846 X E+1
rad (radiation dose absorbed)	Gray (Gy)**	1.000 000 X E–2
roentgen	coulomb/kilogram (C/kg)	2.579 760 X E–4
shake	second (s)	1.000 000 X E–8
slug	kilogram (kg)	1.459 390 X E+1
torr (mm Hg, 0°C)	kilo pascal (kPa)	1.333 22 X E–1

*The becquerel (Bq) is the SI unit of radioactivity; Bp = 1 event/s.

**The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION 1

INTRODUCTION

1.1 BACKGROUND AND OBJECTIVE.

This technical report describes computational modeling of underground tunnel response in support of the Underground Technology Program (UTP) which is a multi-year investigation into the vulnerability of underground structures. The overall program includes computational modeling, material modeling, laboratory testing, and field testing to improve the ability to predict the response and failure of underground structures subjected to ground shock due to near-surface explosions. The emphasis is on deeply buried tunnels with little or no reinforcement.

1.2 SCOPE AND SUMMARY.

The computational modeling effort involved three major areas of investigation: 1) benchmark activity, 2) parametric study and 3) laboratory test simulation. The benchmark activity was a step-by-step series of idealized problems which addressed various aspects of tunnel response in jointed rock masses. The parametric study considered the systematic sensitivity of loading environment, material characterization and geometric conditions as well as computational approaches on tunnel response. Numerical simulation of the SRI International lab-scale HE experiments on tunnel response in intact limestone was conducted to correlate calculational approaches with data.

As one of several participants in the computational modeling effort, it is clear that a step-by-step procedure of material model verification, free-field loading environment definition and parametric response calculations need to be performed in order to reduce uncertainties and improve the ability to predict the response and failure of underground structures subjected to ground shock due to near-surface explosions.

SECTION 2

BENCHMARK ACTIVITY

Various numerical approaches to problems of tunnel dynamics are compared with each other and, wherever possible, with exact analytic solutions by Logicon RDA [Simons, 1992]. The medium is an idealization of a jointed rock mass. The intact rock is linear elastic-plastic with a pressure dependent failure surface and associated plastic flow law. There are two orthogonal sets of equally spaced joints. Each joint is nonlinear elastic in the normal direction and linear elastic with Coulomb friction in shear.

The TRT approach utilizes the EXCALIBUR finite element method [Ito, England & Nelson, 1981] to represent the intact rock and joints with two different types of models for jointed rock, an explicit one where the joints are treated separately (in the near field of the tunnel), and an implicit one where their properties are lumped together with those of the intact rock (in the far field). The TRT implicit joint model admits arbitrary constitutive behavior in both the intact rock and joint, and by enforcing internal compatibility and stress equilibrium derives a super-element representing the combined deformation due to both joints and intact rock.

2.1 PROBLEMS WITH ANALYTICAL SOLUTIONS.

The first five problems are quasi-static driven by boundary displacements which are consistent with homogeneous (uniform) strain throughout the region of interest. This does not mean that the actual strains will be uniform; if there are joints then the actual strains will not be uniform. But in fact the stresses and strains in the intact rock and joint material will separately be homogeneous at each point of the imposed strain path. This opens the possibility of direct analytical solution of these problems for comparison with numerical results.

Another way of viewing the situation is that each of these problems reduces to nothing more than finding the response of a single implicit element around a specified strain path. This is strictly a material response question;

equations of motion or compatibilty among elements play no role whatsoever. It is interesting to note that TRT was the only participant to produce single-element solutions to all of the first five problems.

2.2 TWO-DIMENSIONAL PROBLEMS.

Simplicity makes analytic solutions possible. In contrast the two-dimensional problems have fields which vary both spatially and temporally so that analytic solutions are not generally feasible. The free-field problem concerns deformations of a wedge-shaped section of an annulus in plane strain, as shown in Figure 2-1, with the entire region containing vertically and horizontally jointed rock. The top edge (inner arc) is loaded with the pressure pulse shown in the figure, while shear tractions are zero. The left and right sides have roller boundaries, making the left side a plane of symmetry (the right side is not, because the effective anisotropy due to jointing makes the material unsymmetric about that plane). The lower edge (the outer arc) is a transmitting boundary.

Most of the region is to be modeled implicitly, except for a rectangular region extending 2.5 tunnel diameters (12.5 m) in all directions from the on-axis point at R = 500 m. This region is modeled explicitly, in anticipation of the tunnel situated there in the final problem. The free-field problem is essential to clearly define the loading environment at the tunnel range. The geometry and loading in the final problem are shown in Figure 2-2, which are precisely the same as the free-field problem but now there is a lined tunnel in the center of the rock island.

Based on a combination of physical understanding of wave propagation and material behavior and comparison with the analytic solutions, three of the numerical approaches, including TRT, are judged [Simons, 1992] to have produced credible results to the final problem of a lined tunnel in jointed rock mass engulfed by a cylindrically divergent stress wave.

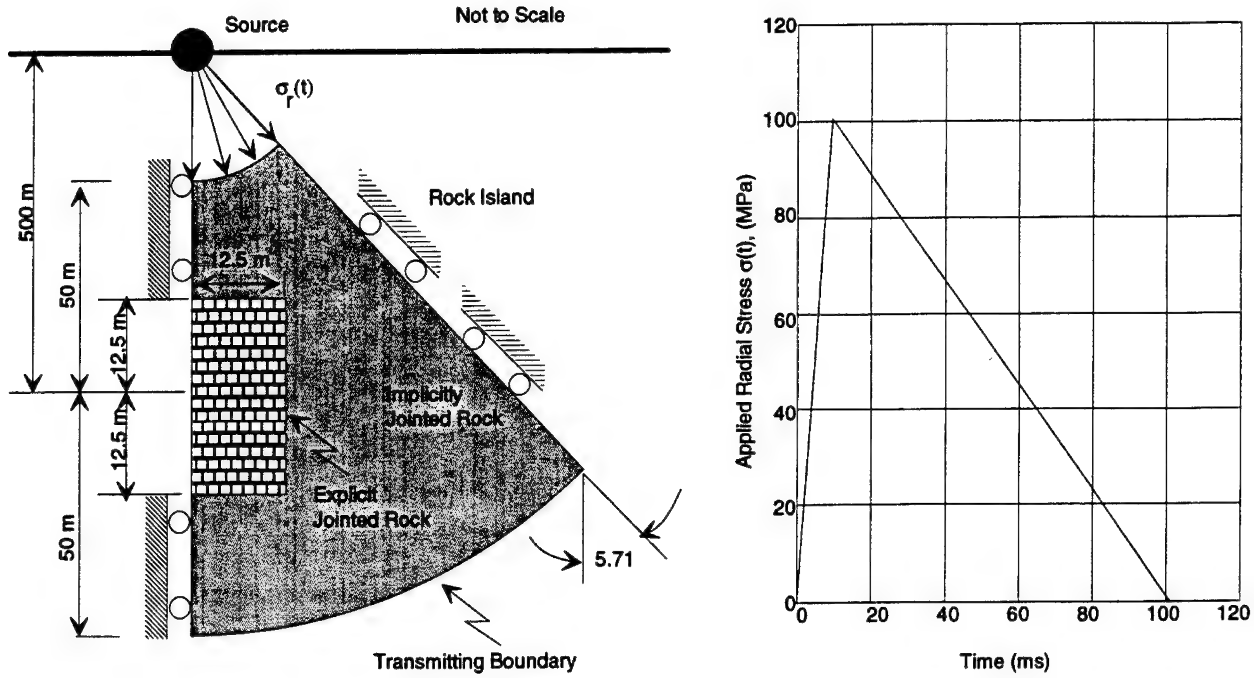


Figure 2-1. Geometry and loading in free-field problem.

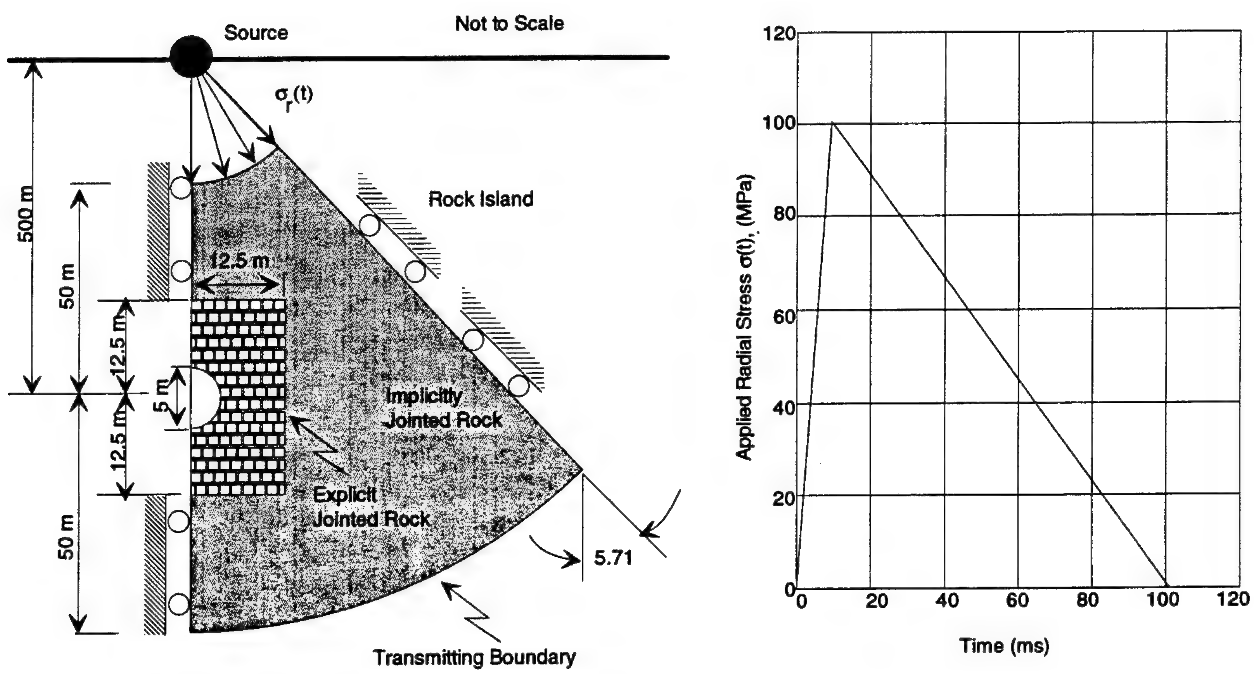


Figure 2-2. Geometry and loading in tunnel problem.

SECTION 3

PARAMETRIC STUDY

The parameter study provides a systematic investigation of the sensitivity of tunnel response to a variety of factors:

- Geometric Considerations
    - range from source
    - diameter
    - divergence

- Loading Environment
    - peak incident stress
    - pulse duration

- Material Characterization
    - dilatancy
    - extension/compression strength ratio
    - flow rule

- Numerical Scheme
    - code

The scope of the study (initially) involves nine independent parameters or 2^9 = 512 two-dimensional calculations using a wedge-shaped computational model and linear elastic-plastic material model similar to that in the benchmark activity but without joints. The participants are Weidlinger Associates (WA) and TRT. The calculational data from the parameter study is analyzed by Logicon RDA [Pucik & Curry, 1993] using design-of-experiments methodologies [Box, Hunter & Hunter, 1978].

3.1 PROBLEM DEFINITION.

The initial problem definition for geometry, material properties, loading and calculation matrix are given in Tables 3-1 to 3-4, respectively.

3.2 CONCLUSIONS.

The key conclusions from this parameter study are as follows:

- Tunnel Failure Sensitive to Three Main Parameters
    - peak incident stress
    - extension/compression strength ratio
    - flow rule

- Crush Strength Not A Very Sensitive Parameter

- Numerical Approach (Calculator) An Important Parameter

- Geometric Scaling Applies
    - range and diameter combined into single parameter
    - if and only if numerical grid scaled geometrically

Table 3-1. Geometry.

Property	Symbol	Value(s)	
Range of tunnel from source	R	250 m	500 m
Tunnel diameter	D	5 m	10 m
Liner thickness	h	D/100	

Table 3-2. Material Properties.

Property	Symbol	Value(s)	
Rock mass density	ρ	2500 kg/m^3	
Rock Young's modulus	E	30 GPa	
Rock Poisson's ratio	ν	0.25	
Rock cohesion	c_o	4.5 MPa	
Rock friction angle	ϕ	25°	
Rock dilation angle	ψ	25°	0°
Rock extension/compression strength	σ_e / σ_c	0.5	1
Rock tensile strength	T_o	2 MPa	
Rock critical pressure	P_c	66.7 MPa	133.3 MPa
Rock uniaxial tangent modulus	M^t	24 GPa	
Rock cap aspect ratio	R_{cap}	2.5:1	
Liner Young's modulus	E_L	200 GPa	
Liner Possion's ratio	ν_L	0.30	
Liner yield strength	σ_Y	400 MPa	
Liner mass density	ρ_L	7500 kg/m^3	

Table 3-3. Loading.

Parameter	Symbol	Value(s)	
Peak incident stress	σ_o	100 Mpa	200 Mpa
Positive phase duration of velocity relative to DUG-1C	t_+/t_{+DUG}	1	0.5
Wavefront divergence	R/R_{wf}	0	1

Table 3-4. Calculation Matrix.

Run	R (m)	σ_o (MPa)	ψ (deg)	t_+/t_{+DUG}	D (m)	σ_e/σ_c	P_c (MPa)
1	500	200	25	1	10	1	133.3
2	500	200	25	0.5	5	0.5	133.3
3	500	200	0	1	5	0.5	66.7
4	500	200	0	0.5	10	1	66.7
5	500	100	25	1	10	0.5	66.7
6	500	100	25	0.5	5	1	66.7
7	500	100	0	1	5	1	133.3
8	500	100	0	0.5	10	0.5	133.3
9	250	200	25	1	5	1	66.7
10	250	200	25	0.5	10	0.5	66.7
11	250	200	0	1	10	0.5	133.3
12	250	200	0	0.5	5	1	133.3
13	250	100	25	1	5	0.5	133.3
14	250	100	25	0.5	10	1	133.3
15	250	100	0	1	10	1	66.7
16	250	100	0	0.5	5	0.5	66.7

SECTION 4

LABORATORY TEST SIMULATIONS

SRI International performed both static tunnel tests [Simons et al, 1993] and spherical wave tunnel (SWAT) tests [Klopp et al, 1993] in limestone blocks to compare the measured loading environment and tunnel closures with those from various computational models. The TRT approach utilizes relatively fine zoning to capture the free-field environment with ten circumferential elements across the tunnel radius and radial elements one-fifth of the radius near the tunnel, while the liner is a simple membrane. Both two-invariant and three-invariant failure models are developed for the limestone based on the RE/SPEC material properties [Fossum, 1993]. All numerical simulations were performed 'pre-test' before the measured data were made available. In addition, preliminary calculations were conducted to verify the computational approach and material modeling.

4.1 STATIC TUNNEL TESTS.

Three static tunnel tests in limestone are simulated, called ST1, ST2, and ST3. The limestone specimens are cylinders 30.5 cm (12 in.) in diameter with a tunnel located at the specimen midheight. The height of the specimen for ST1 is 30.5 cm (12 in.) and the tunnel is unlined and has a diameter of 19.1 mm (0.750 in.). For ST2 and ST3 the specimen height is 45.8 cm (18 in.) and the tunnels are lined (fully annealed 3003 aluminum tube with 70 MPa strength). The specimens are loaded by two independent hydraulic pressures, a vertical load applied to the top and bottom surfaces of the cylinder and a confining load around the outer surface of the cylinder. For ST1 and ST3 the loading history is a single cycle of loading (191 MPa and 139 MPa, respectively) and unloading. For ST2 the specimen is loaded to 125 MPa, unloaded, reloaded to 156 MPa, and then unloaded.

The closure comparisons of the numerical simulations of ST1 using two-invariant (M-S) and three-invariant (W-W) strength models based on RE/SPEC-93 properties show little difference at the crown-invert (Figure 4-1) but a factor of three increase at the springline (Figure 4-2) due to strength reduction (70%) in TXE , which is more consistent with the measured closure data. Numerical

simulations of ST2 produce similar results as ST1 since the confining conditions are essentially uniaxial strain with no shear failure in the far-field at the loading boundary. In contract, both the numerical simulations and laboratory experiments of ST3 are very sensitive and produce a wide variation in tunnnel closure due to the divergent loading which can induce shear failure in the whole specimen.

4.2 SPHERICAL WAVE TUNNEL TESTS.

The spherical wave tunnel (SWAT) tests involve a charge of PETN detonated in a block of limestone containing tunnels. The numerical simulations involve the two initial/boundary value problems given in Figure 4-3. The problems are identical except for the location of the tunnel, either 14.5 cm or 19.5 cm from the center of the charge. The measured particle velocity history shown in the figure is applied to the inside of the 7.50-cm radius cavity.

A rate-enhanced three-invariant (W-W) failure with symmetric crush (Cap) model consistent with RE/SPEC and ARA static (10^{-5}/s) data, ARA extrapolated dynamic (10^{+2} - 10^{+3}/s) strength data and LLNL shock hugoniot (10^{+4}/s) crush data is developed for numerical simulation of SWAT. Assuming log-linear interpolation with no SWAT free-field data, this uncalibrated rate-enhanced model gives about a factor of two increase in crush strength (initial cap location) and 33% increase in shear strength.

The rate-enhanced model is also calibrated using log-bilinear interpolation to match SWAT (10^{+2}/s - 10^{+3}/s) free-field environment at both the particle velocity stations (Figure 4-4) as well as the stress at the range of the tunnels (Figure 4-5). The comparison of the calibrated rate-enhanced response to the measured data at the 14.5-cm tunnel is 8% versus 7% crown-invert closure (Figure 4-6) and 4% versus 2% springline closure (Figure 4-7). This is a very good comparison given the uncertainty in strain-rate effects on shear strength including extension/compression strength ratio. It should be noted that while the rate independent model appears to give better correlation with measured springline closure (Figure 4-7), this is very misleading since this model does not reproduce the measured free-field loading environment (Figures 4-4 and 4-5).

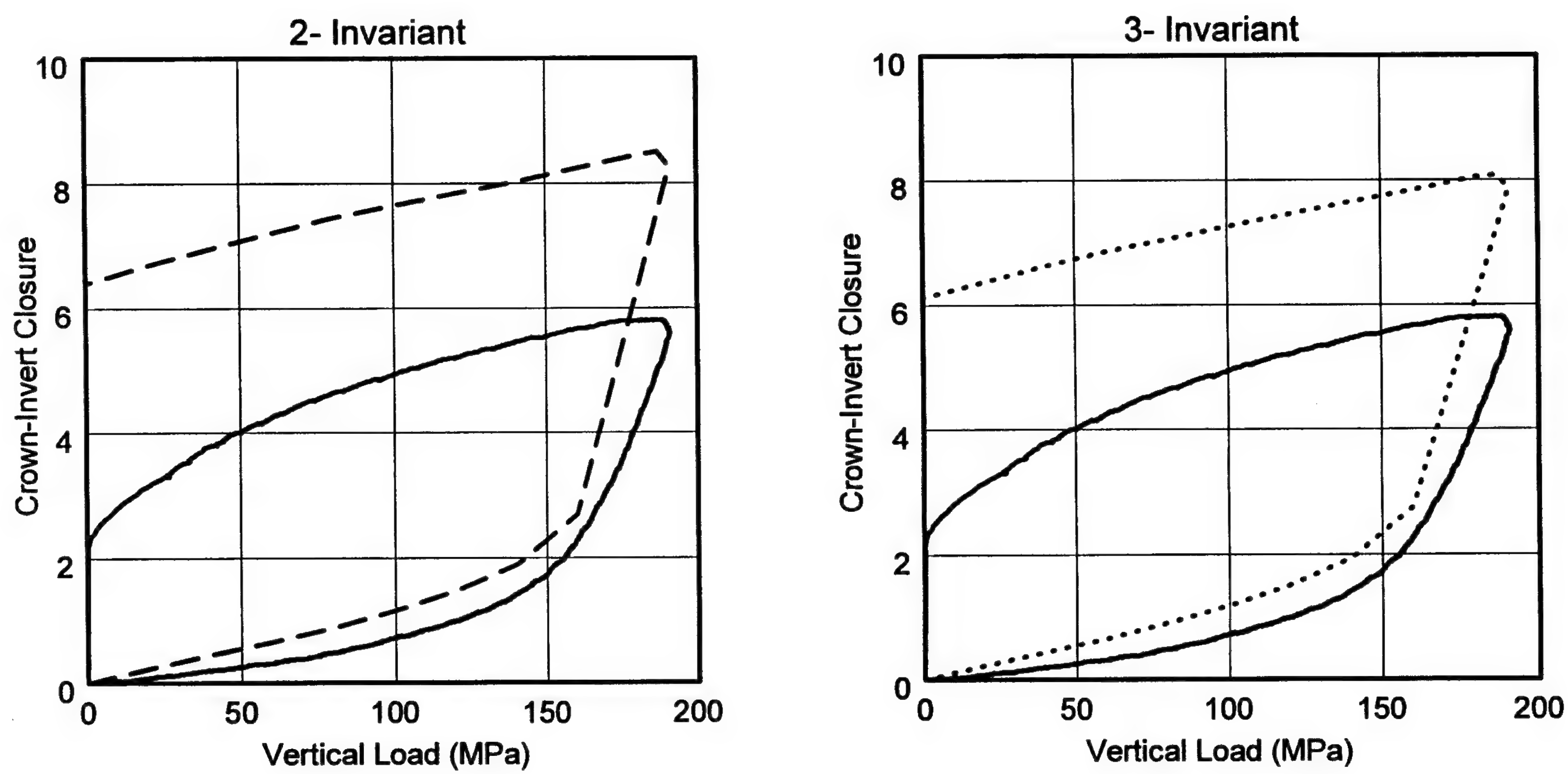


Figure 4-1. Crown-Invert closure - ST 1.

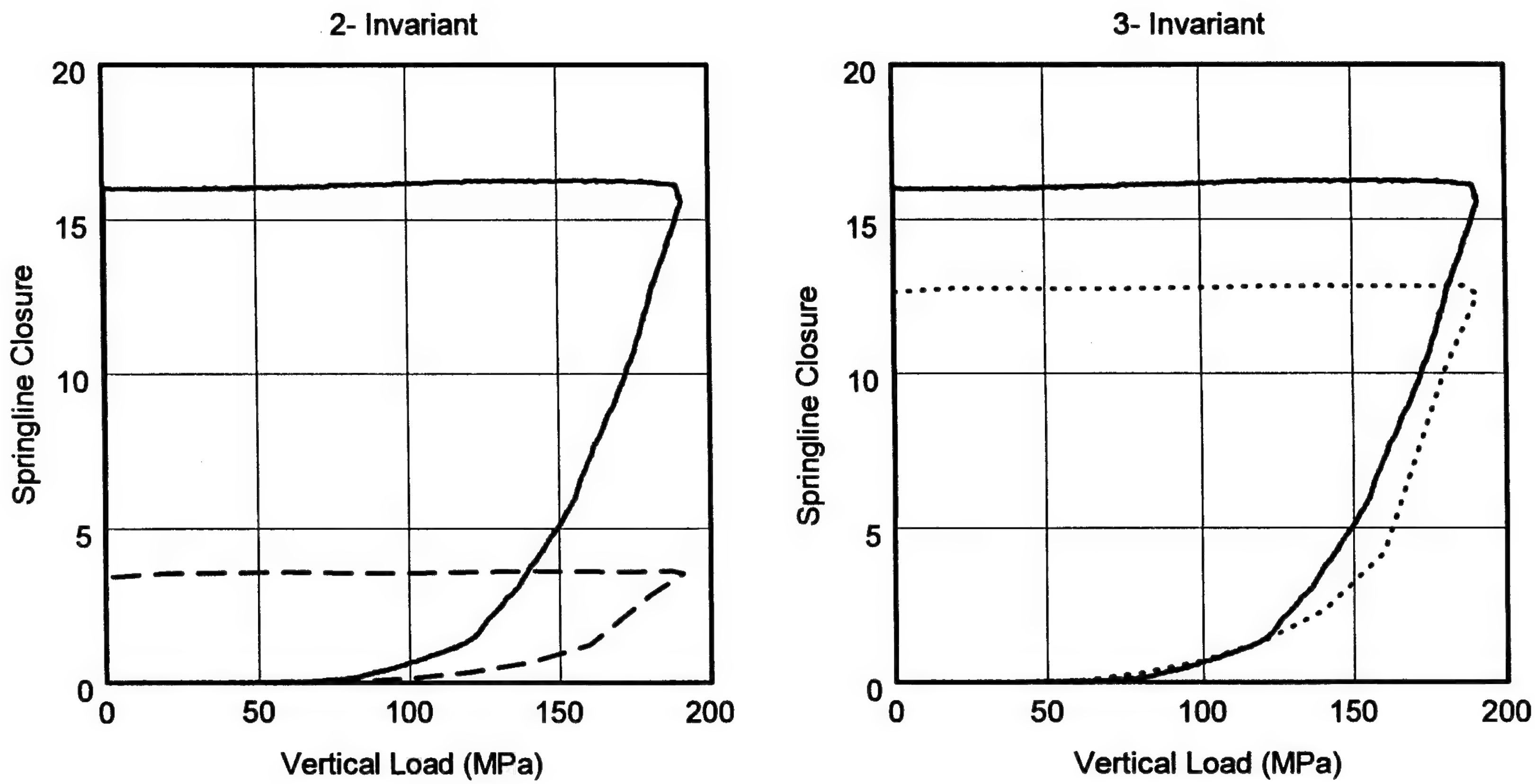
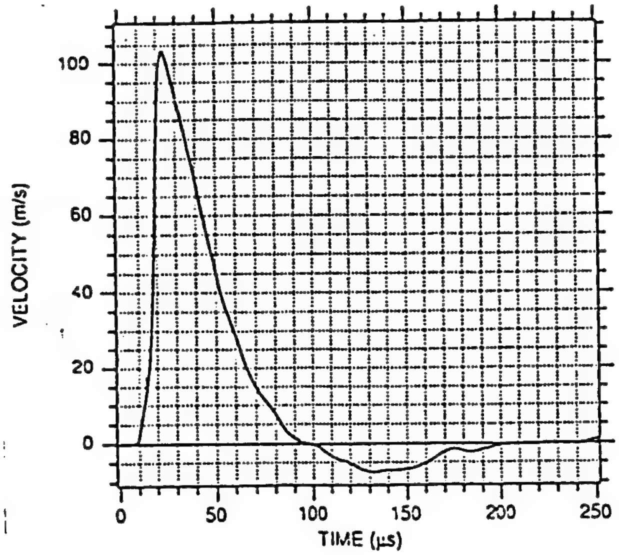


Figure 4-2. Springline closure - ST 1.



Gage	z (cm)
PV2	8.33
PV3	10.00
PV4	11.67
PV5	13.33
PV6	15.00
PV7	16.67
PV8	18.33
PV9	20.00
PV10	21.67
PV11	23.33

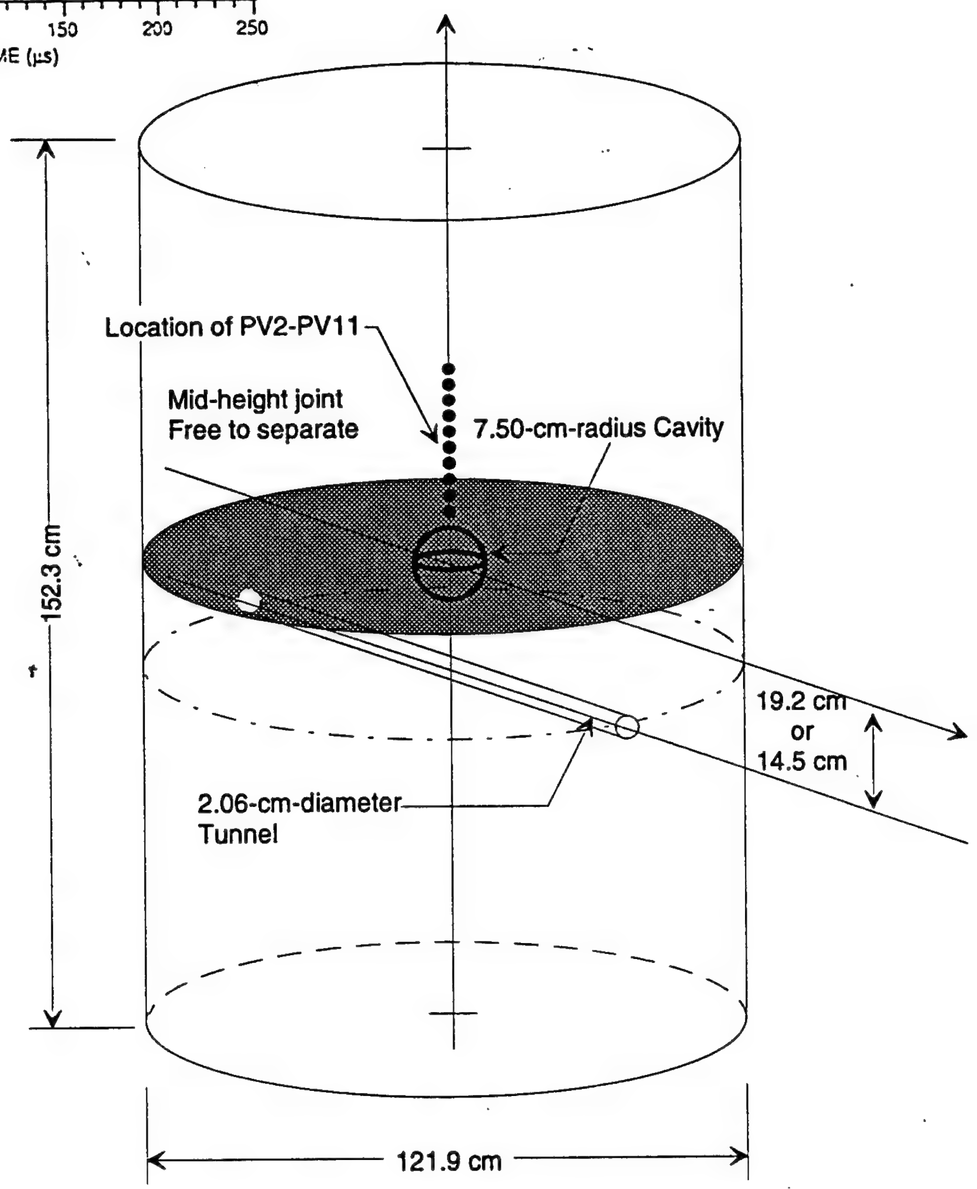


Figure 4-3. SWAT Initial/boundary value problem.

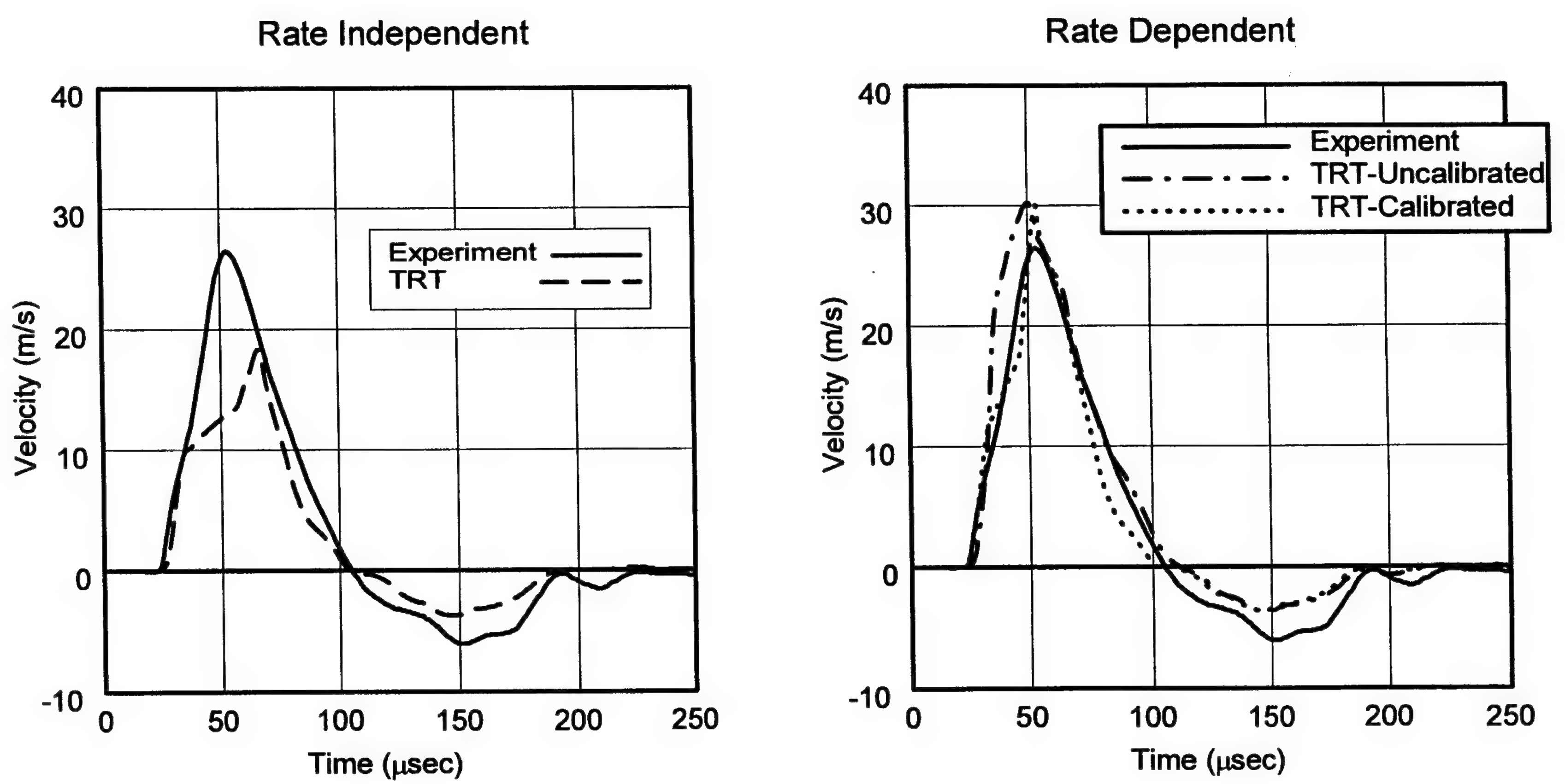


Figure 4-4. Free field velocity - PV5 (13.33 cm).

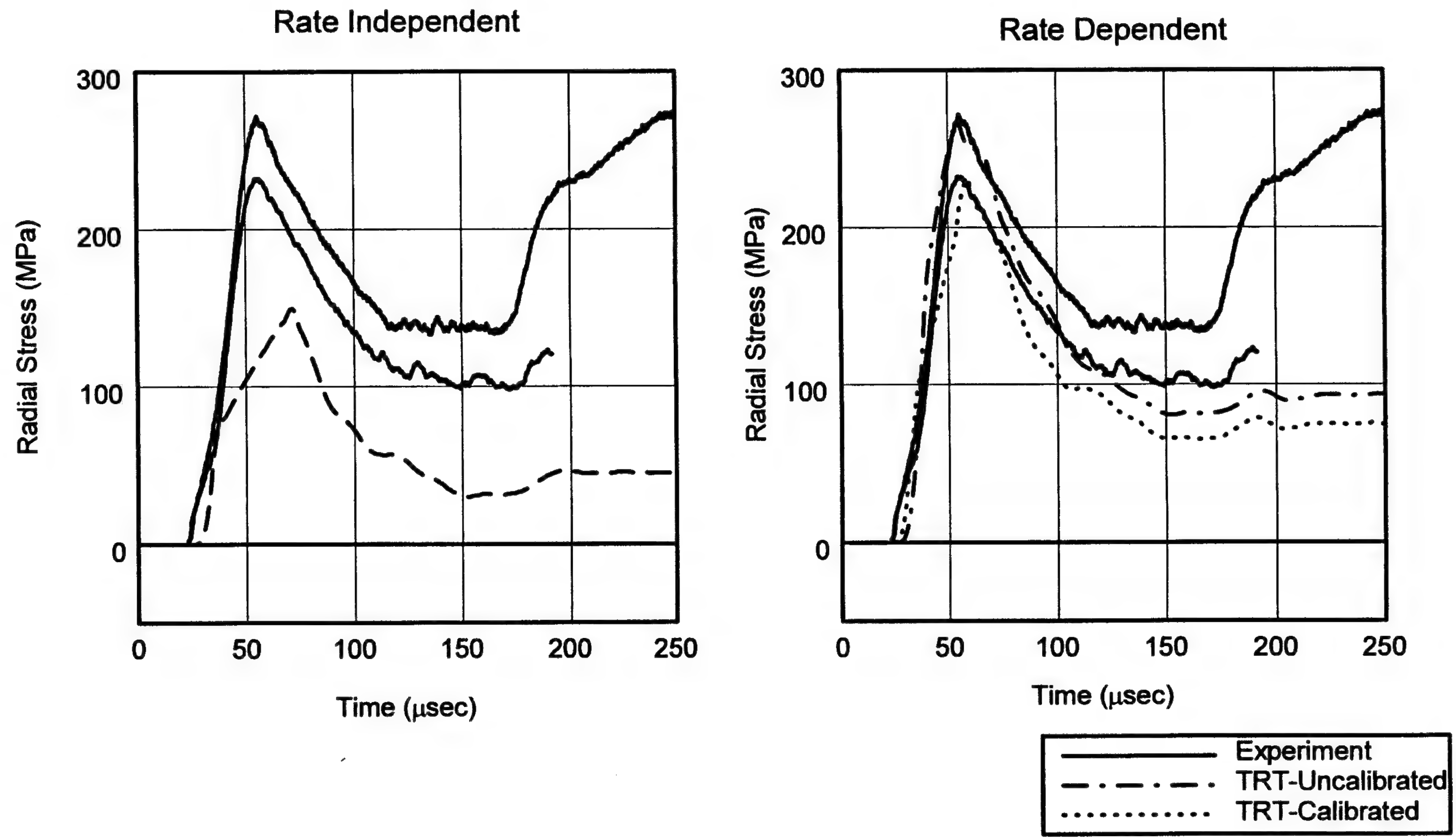


Figure 4-5. Free field radial stress - 14.5 cm.

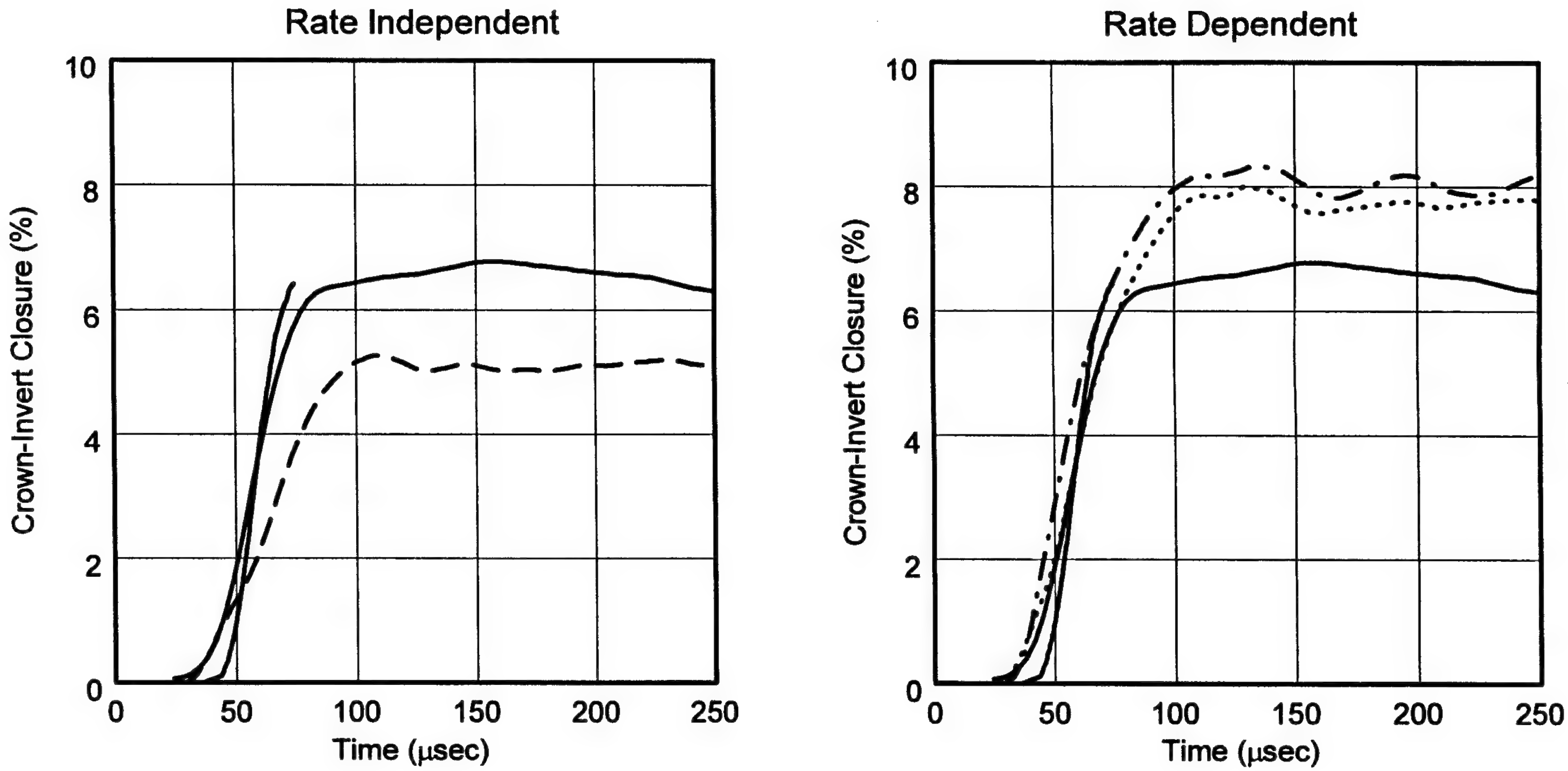


Figure 4-6. Crown Invert Closure - 14.5 cm.

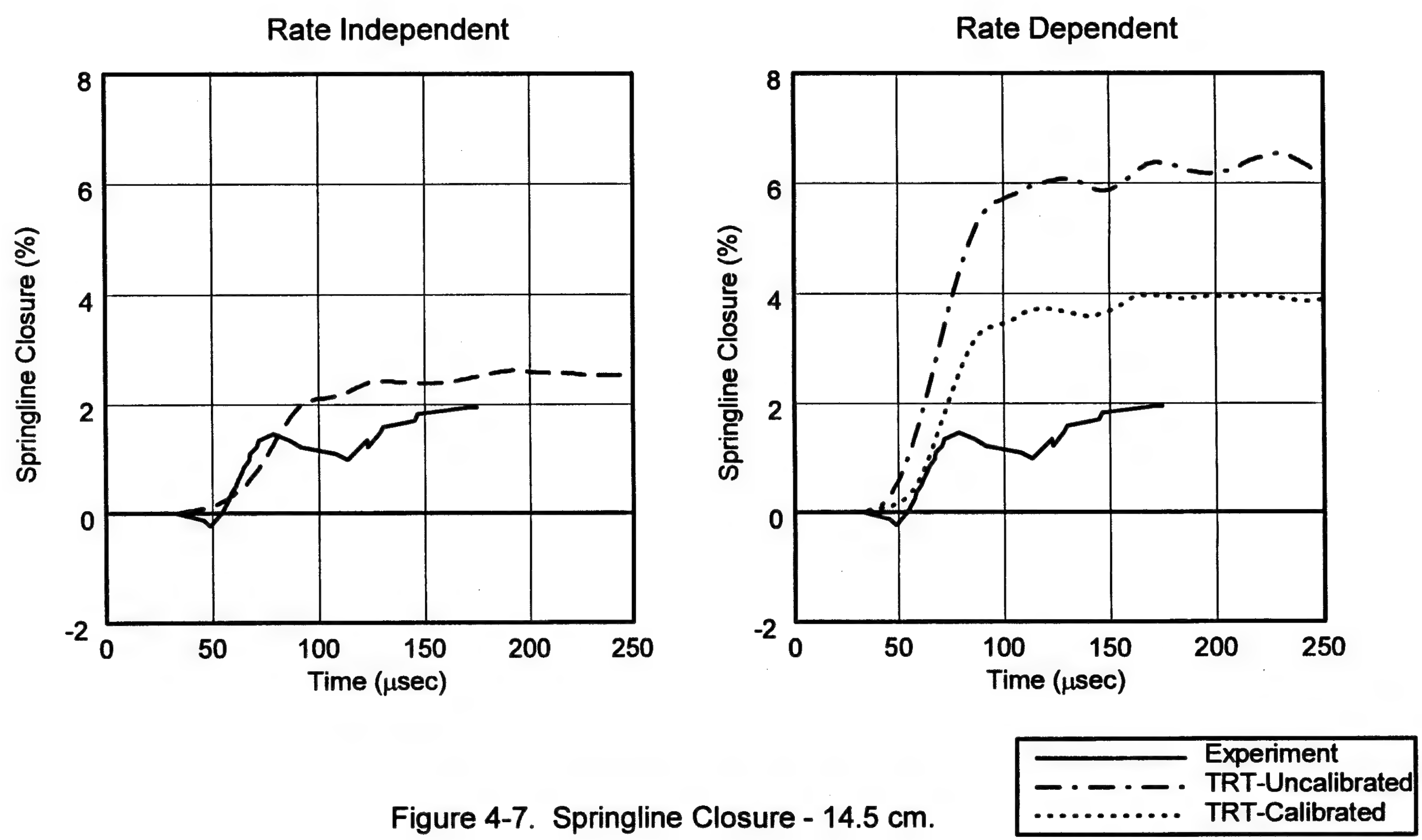


Figure 4-7. Springline Closure - 14.5 cm.

SECTION 5

RECOMMENDATIONS

As one of several participants in the computational modeling effort, it is clear that a step-by-step procedure of material model verification, free-field loading environment definition and parametric response calculations need to be performed to reduce uncertainties and improve the ability to predict the response and failure of underground structures subjected to ground shock due to near-surface explosions. A major uncertainty is strain-rate effects on shear strength including extension/compression strength ratio of rocks of interest.

SECTION 6

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